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TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

TRECOM TECHNICAL REPORT 63-61

EXPERIMENTAL INVESTIGATION OF THE VISCOUS EFFECTS ON BALANCED JETS IN GROUND PROXIMITY

Task 1D021701A04804
(Formerly Task 9R99-01-005-04)
Contract DA 44-177-TC-845

October 1963

prepared by:

HYDRONAUTICS, Incorporated
Laurel, Maryland

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HEADQUARTERS
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This is the final report on an investigation of the flow of air jets in ground proximity. Two previous reports presented a theory which includes the effects of viscosity of the air on balanced and unbalanced two-dimensional jets. This report presents the results of an attempt to verify experimentally the assumptions of the theoretical model.

The results of this experimental investigation indicate that the vortical flow induced by the viscosity of an air jet can be represented with engineering accuracy by the assumption of uniform vorticity for the case of a balanced peripheral jet. The flow pattern of the unbalanced peripheral jet was not determined experimentally.

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EXPERIMENTAL INVESTIGATION OF
THE VISCOUS EFFECTS ON BALANCED
JETS IN GROUND PROXIMITY

Technical Report 241-3

Third of a Series of Reports Pertaining to the Investigation of Air Jet Flow Fields in Ground Proximity

Prepared by
HYDRONAUTICS, Incorporated
Laurel, Maryland

for
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

PREFACE

The work reported herein was conducted at HYDRONAUTICS, Incorporated under U. S. Army Transportation Contract Number DA 44-177-TC-845. This report is the third to be issued under this contract and represents the conclusion of the work to be conducted under this contract. The work was carried out and the report written by E. S. Curtis and V. R. Pfisterer. The technical administrative representative of the U. S. Army Transportation Research Command for this project was Mr. William D. Hinshaw.

CONTENTS

ILLUSTRATIONS

SYMBOLS

H	height of the nozzle above the ground
$\overline{H}$	non-dimensional height of the nozzle above the ground, $\overline{H} = \frac{H}{t}$
p_a	atmospheric pressure
p_b	absolute base pressure
t	nozzle thickness
$\overline{V}_j$	average jet velocity
V_v	induced velocity in the vortex
x	distance from the nozzle to the pressure tap
z	distance from the nozzle to the point on the ground where the dividing streamline impinges

SUMMARY

This report covers an experimental investigation of the flow field beneath a two-dimensional ground effect machine and in the vicinity of its peripheral jet for various nozzle heights. The purpose of this investigation was to provide experimental information for comparison with the theoretical results presented in HYDRONAUTICS, Incorporated Technical Report 241-1 (1). Specifically, the shape and location of impingement on the ground of the dividing streamline were determined; measurements of the approximate size and shape of the base vortex were made along with vorticity and velocity measurements; and measurements of pressures along the base of the machine were made. All of these experimental results are compared with the theory presented in (1).

CONCLUSIONS

This experimental investigation of a two-dimensional ground effect machine serves to complement the analytical studies presented in (1) and further contributes to a more thorough understanding of the aerodynamic phenomena associated with peripheral air jet flow fields in ground proximity. The mean flow pattern was determined to be that of a turbulent diffusing jet which is deflected laterally in its interaction with the central pressure zone. Under the nozzle base, this leads to the formation of a vortex standing alongside the main jet. Observed characteristics of the dividing streamline and base pressure measurements were found to be in good agreement with the theoretical calculations presented in (1). The experimental results also revealed that, in order to have a more exact quantitative correlation between the present data and theory, the effect of the non-uniformity of vorticity and of a possible secondary (corner) vortex should be taken into account.

INTRODUCTION

Within the last decade, considerable theoretical and experimental effort has been directed towards the understanding of the basic principles governing the performance of ground effect machines. The majority of the theories which have been proposed have neglected the effect of turbulent mixing and vortex generation on the jet configuration and base pressure distribution. In HYDRONAUTICS, Incorporated Technical Report 241-1 (1), these effects have been included in the derivation of a theory for the viscous effects on balanced jets in ground proximity. For this derivation, it was necessary to make certain assumptions and approximations regarding the jet behavior and mean flow pattern. It was felt that these assumptions and the results which they yielded should be checked by an experimental study and, if necessary, the theory revised to include this new information. This report deals with such an experimental investigation of the flow field beneath a two-dimensional ground effect machine and in the vicinity of its peripheral jet.

Figure 1 shows a pair of two-dimensional nozzles joined by a base plate. When these nozzles are in ground proximity, the pressure between the base plate and the ground will increase so as to cause the jets to flow outward. For reasons of symmetry, a wall along the centerline of the base plate, as shown in Figure 2, will also yield the same flow for a symmetric ground effect machine. A model of this type, with the nozzle discharging vertically, was used in these studies.

One of the areas of interest for which experimental investigations were made was that of the two-dimensional jet issuing from the nozzle. In (1), it was assumed that the velocity distribution and entrainment processes for the jet were the same as those for a single turbulent jet discharging into an infinite fluid. The curvature of the jet was specified to be constant until the dividing streamline impinged on the ground. The velocity distributions in the jet just before and after impingement were assumed

DESCRIPTION OF THE MODEL AND THE AIR SUPPLY SYSTEM

The model which was used to simulate two-dimensional flows under a ground effect machine consisted of a vertically discharging nozzle attached to a plexiglass box-like section. A sketch of the model is shown in Figure 3. A photographic view of the model is shown in Figure 4. The height of the nozzle above the ground was varied by placing plywood spacer sections on the ground board.

For all of these tests, the jet flowed out of the nozzle with an exit angle of 0° from the vertical and a thickness of $\frac{1}{2}$ inch. A velocity traverse along the length of the 22-inch nozzle showed that the flow in the central region of the jet was two-dimensional.

The walls of the plexiglass model were $\frac{1}{4}$ inch thick. Its total length was 48 inches, 24 inches of it forming a closed channel representing a section of the area beneath a two-dimensional ground effect machine. The remaining 24-inch distance consisted of two parallel walls (without roof), representing a section of the area outboard of a two-dimensional ground effect machine, to ensure an adequate length for the establishment of the flow. Pressure taps were located along the roof of the model so that the effect of the vortex on the base pressure distribution could be observed.

Figure 5 shows the air feed system to the model. Air was supplied to a stilling chamber by means of a turbo compressor which has a maximum capacity of 25 c.f.s. at 54 p.s.f.

When the jet discharged vertically, that is, when the model was in its normal position, the air from the stilling chamber flowed into two air feed pipes. From these, the flow was turned 90° through vanes to the air intake section and model. The discharge to the model had been previously calibrated against centerline readings in the air inlet pipes. Figure 6 is a photograph of the model in its normal position.

For some of the flow visualization studies, it was found convenient to turn the model on its side so that the jet discharged horizontally. As can be seen from Figure 5, for these cases the model was attached directly to the stilling chamber. Figure 7 is a photograph of the model on its side.

TEST PROCEDURE AND EXPERIMENTAL RESULTS

The main areas of interest of the jet and its mean flow pattern that were studied were the dividing streamline, the base vortex, and base pressures. Test procedures are presented in the following sections along with the experimental results and comparisons with theory.

DIVIDING STREAMLINE STUDIES

The location of the point on the ground at which the dividing streamline impinges was obtained for a range of nozzle heights. For these studies a paint drop technique was used. Two lines 1/2 inch apart, corresponding to the thickness of the nozzle, were painted on a piece of plexiglass and positioned on the ground directly beneath the nozzle. Paint drops were placed in staggered rows on the plate in the general vicinity where the dividing streamline was believed to impinge. The air was supplied to the model and the drops flowed in the resultant flow direction; the point of impingement of the dividing streamline was located between those drops which flowed in opposite directions. Figure 8 is a photograph of a typical jet impingement run. Shown in Figure 9 is a comparison between the experimental locations of the dividing streamline impingement and the locations predicted by the theory reported in (1). It should be noted that agreement between theory and experiment is excellent.

Flow visualization studies were also conducted in the vicinity of the jet to determine its characteristic flow pattern. For these tests the model was positioned on its side so that the jet discharged horizontally. A plexiglass plate with paint drops on it was held in a horizontal position. The edge of the plate that was against the nozzle was filed to a sharp edge from the lower surface so that there was no disturbance to the flow on the upper surface where the paint drops were applied. The width of the plate was always made somewhat less than the height of the nozzle above the ground so that if there were any cross flow along the ground, it would escape under the plate and not disturb the flow of the paint drops.

Shown in Figures 10a, 11a, and 12a are paint flow studies of the jet and the vortex. As the jet discharged from the nozzle, air was entrained on both sides of its boundaries due to turbulent mixing action, and the jet expanded as it approached the ground. The shape of the dividing streamlines shown in Figures 10c, 11c, and 12c was obtained by scaling the photographs in Figures 10a, 11a, and 12a. In the central and upper portions of the vortex, the paint drops did not move because of the relatively lower velocities there; but in the region of the corner eddy and near the ground, higher velocities occurred and flow directions can be observed from the paint drop studies.

BASE VORTEX STUDIES

In order to determine qualitatively the size and shape of the base vortex, the location of its core, and the approximate direction of flow, a method was devised to study the vortex visually. In the same manner that paint-drop studies were made to determine the shape of the dividing streamline, a plate was inserted horizontally into the model, with the model on its side so that the jet exited horizontally. A shallow pool of water was poured onto the plate and fine plexiglass fillings were sprinkled on the water. After air had been supplied to the model for a short time and the vortex was clearly visible, a photograph was taken with a camera shutter speed of approximately 1/25 second. The results of these studies are presented in Figures 10b, 11b, and 12b, as photographic views of the vortex for non-dimensional nozzle heights, $\frac{H}{t}$, of 4, 8, and 12.

In order to investigate the vortex more thoroughly, a vorticity meter was made and used to determine qualitatively the distribution of vorticity in the region behind the jet. The vorticity meter, shown in Figure 13, had eight 3/8-inch-square blades mounted on a 1/4-inch-diameter ball bearing, the overall outer diameter of the meter being 1 inch. The rotational speed of the vorticity meter was determined with the use of a stroboscope. Plots of constant rotational speed of the vorticity meter are presented in Figures 10c, 11c, and 12c for non-dimensional nozzle heights of 4, 8, and 12.

Also, a vertical velocity traverse through the approximate center of the vortex was made with a 1/8-inch diameter Pitot-static probe. The induced velocity in the vortex non-dimensionalized with respect to the average jet velocity, $\frac{V_v}{\overline{V}_j}$, is plotted in Figures 10c, 11c, and 12c, superimposed on the vorticity plots, for non-dimensional nozzle heights of 4, 8 and 12.

Based on the studies described above, the vortex formed beneath a ground effect machine adjacent to the jet may be generally described as follows.

From both the photographic views of the vortex and from the vorticity measurements, it may be concluded that the principal vortex extends from the ground to the base plate and that its width is from 50 to 100 percent greater than its height. From the photographic views of the vortex, it is seen that the vortex core lies in the vicinity of the geometric center of this vortex. The vorticity plots indicate a non-uniform distribution of vorticity, the latter being stronger toward the intersection of jet and ground than elsewhere. The induced velocities in the region above the core are on the order of 10 to 20 percent of the average jet velocity. In the region very near the ground, it may be seen that very high ($40\% \overline{V}_j$) velocities occur, as also indicated by the paint-drop studies. Again, it is possible from velocity measurements to locate the core approximately at the geometric center, since the velocity was found to be approximately zero there.

It should be recognized that the theoretical first-order analysis of the standing vortex as presented in (1) is based on the assumption that the vortex is square in shape and has uniform vorticity. It is evident from the preceding discussion of experimental results that the effect of non-uniform vorticity should be included if possible in further theoretical analyses of the standing vortex pattern. At the same time, it should be noted that the measured velocity profile reveals that the velocity does increase outward from the center of the vortex as assumed in (1) and consistent with the assumption of uniform vorticity, in contrast to the velocity field of a point irrotational vortex at the center, as had been assumed in previous studies of the subject.

BASE PRESSURE MEASUREMENTS

Base pressure measurements were made in the region behind the jet along the centerline of the model using static pressure taps located in the model base plate. Plotted in Figures 14, 15, and 16 are base pressure measurements determined experimentally for non-dimensional nozzle heights, $\frac{H}{t}$, of 2, 8, and 16; the distance of the tap behind the jet has been non-dimensionalized with respect to the height of the nozzle above the ground. From these plots, it is seen that at all three heights the reduction in base pressure in the region immediately behind the jet due to the vortex occurs over a width from 50 to 100 percent greater than the height of the nozzle above the ground. Widths of the vortex determined by this method are in agreement with widths as determined from the photographic views of the vortex and from the vorticity measurements. Presented along with the experimental data are the theoretical base pressure distributions as determined from (1) using the width of the major standing vortex as one and one-half times the height of the nozzle above the ground. In general, the results are in good agreement (discrepancies range from 4 to 7%). The maximum reductions in base pressure in the vortex region from theory and experiment are also found to be of the same order of magnitude. It should be noted that the width of the vortex is assumed to be one machine height in the numerical calculations of (1). The augmentation factor from these calculations is approximately the same as that using a modified width of the vortex equal to one and one-half times the height of the nozzle above the ground.

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1. "Viscous Effects on Balanced Jets in Ground Proximity", HYDRONAUTICS, Incorporated Technical Report 241-1, Issued Under TRECOM Contract DA 144-177-TC-845, October 1963.

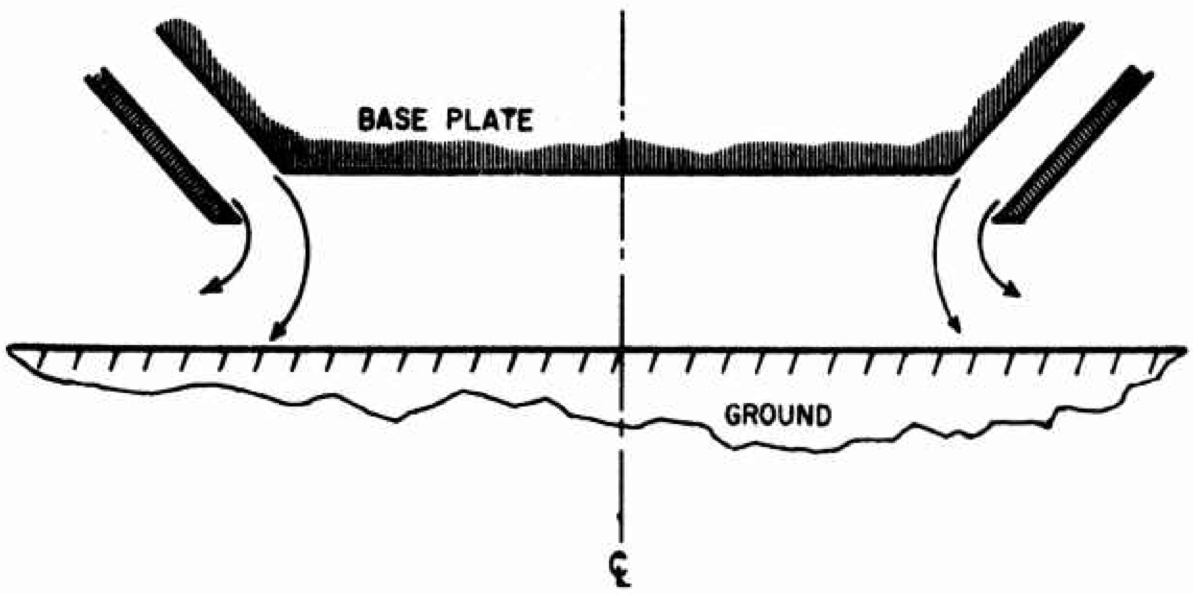


FIGURE 1 - TWO-DIMENSIONAL REPRESENTATION OF PERIPHERAL JET *GEM*

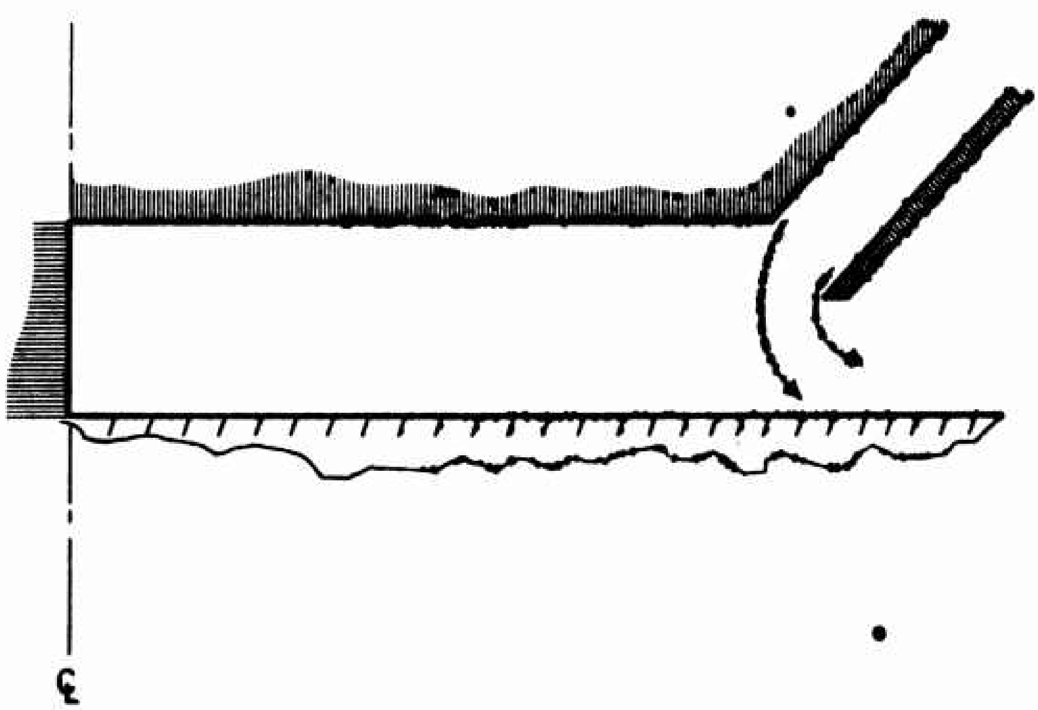


FIGURE 2 - HALF-MODEL OF TWO-DIMENSIONAL PERIPHERAL JET GEM

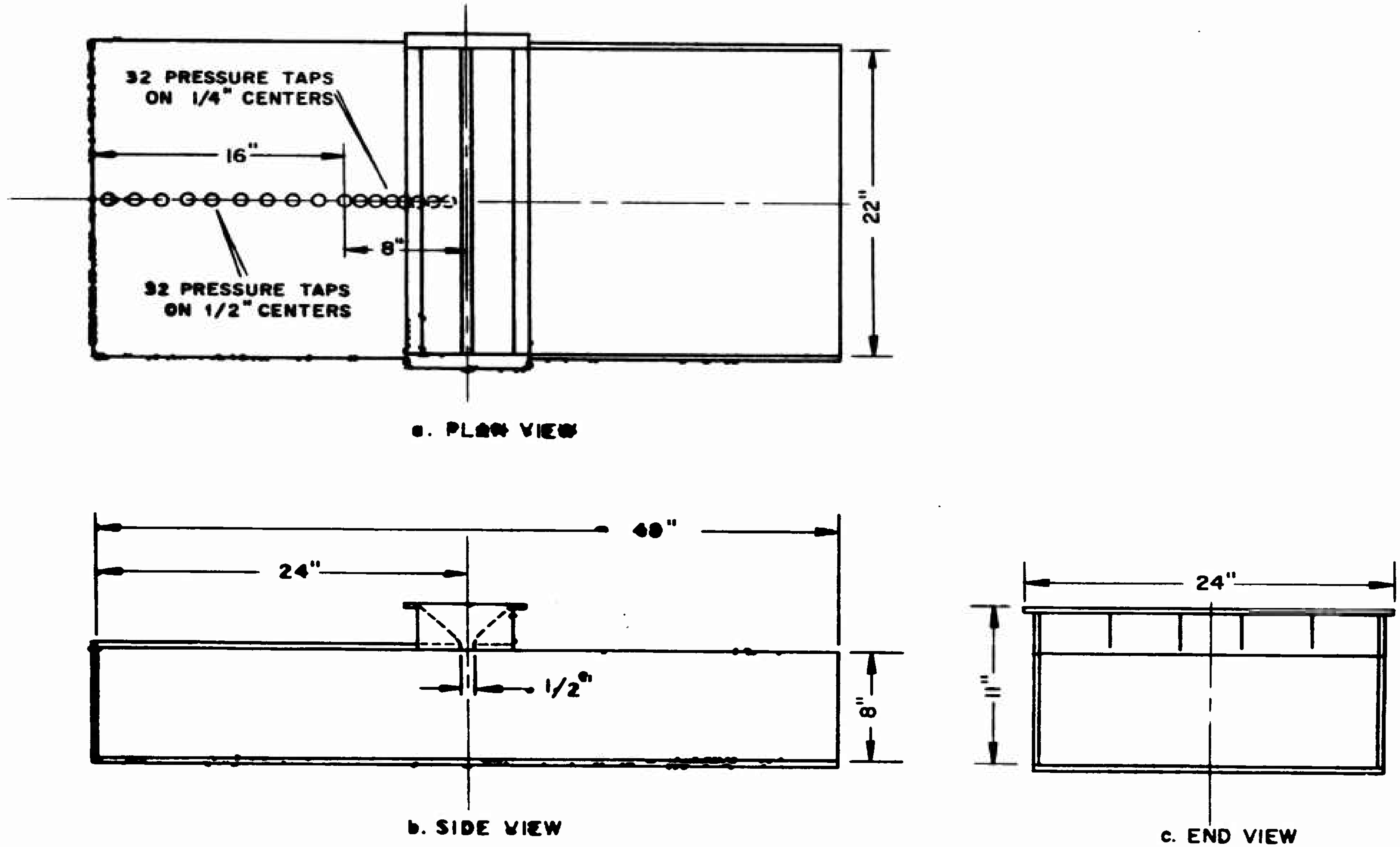


FIGURE 3 - THREE-VIEW SKETCH OF MODEL

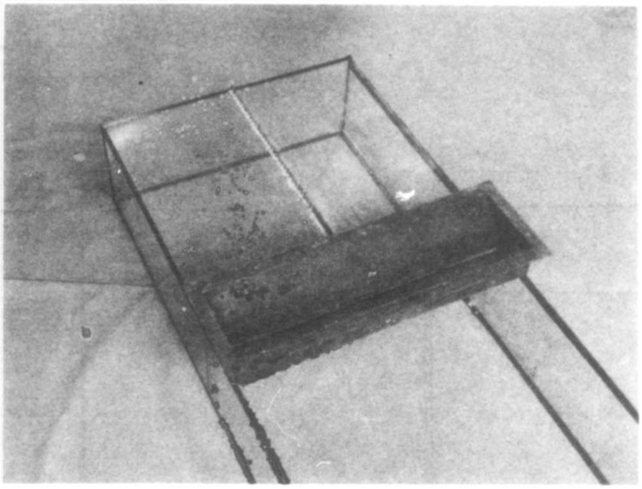


FIGURE 4-PHOTOGRAPHIC VIEW OF MODEL

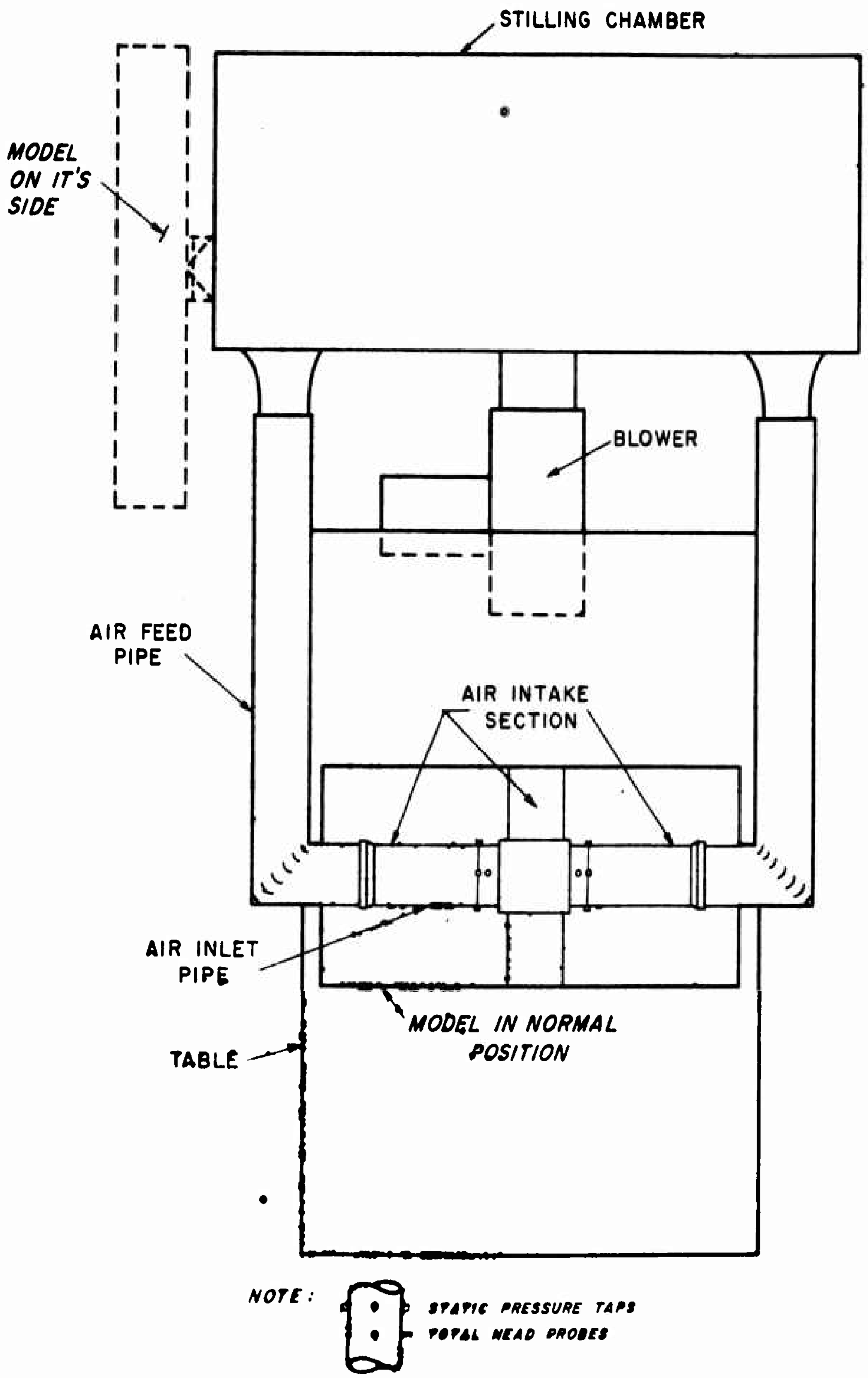


FIGURE 5 - PLAN VIEW OF TEST FACILITY

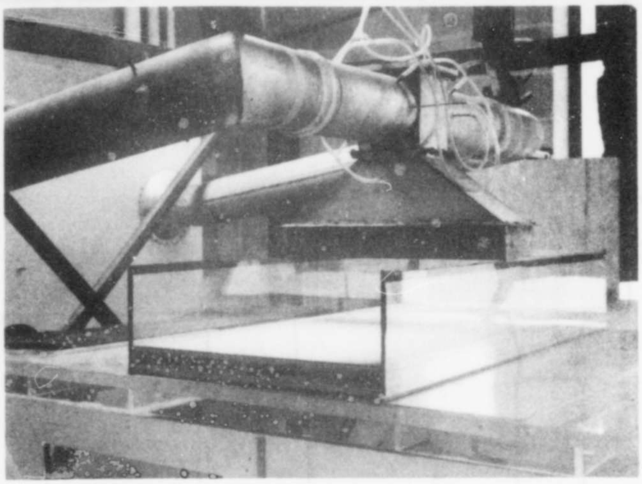


FIGURE 6-PHOTOGRAPH OF MODEL IN THE NORMAL POSITION

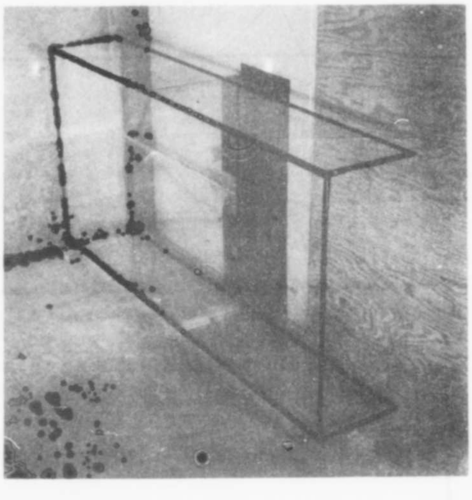


FIGURE 7-PHOTOGRAPH OF MODEL ON ITS SIDE

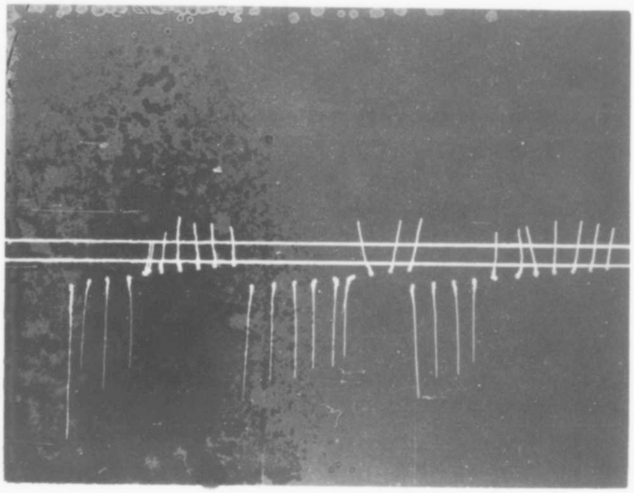


FIGURE 8 - PHOTOGRAPH OF A TYPICAL JET IMPINGEMENT STUDY

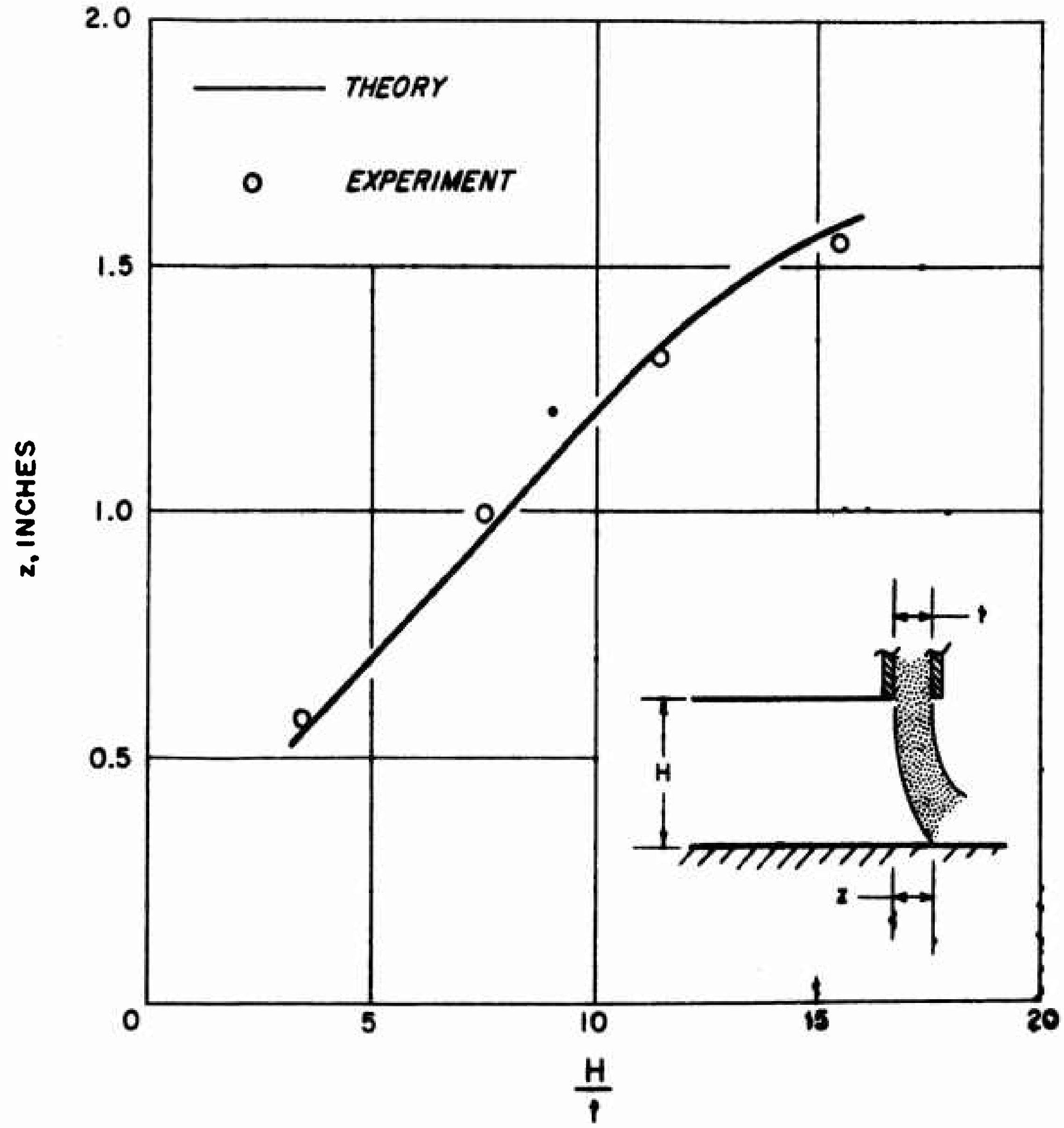
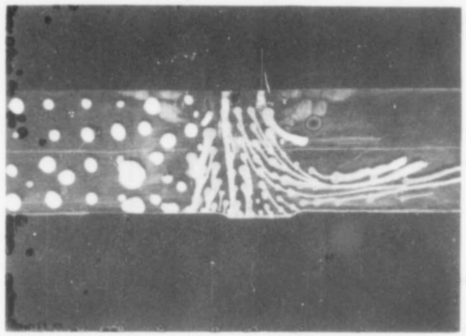


FIGURE 9 - LOCATION OF IMPINGEMENT OF DIVIDING STREAMLINE
$(t = \frac{1}{2}")$



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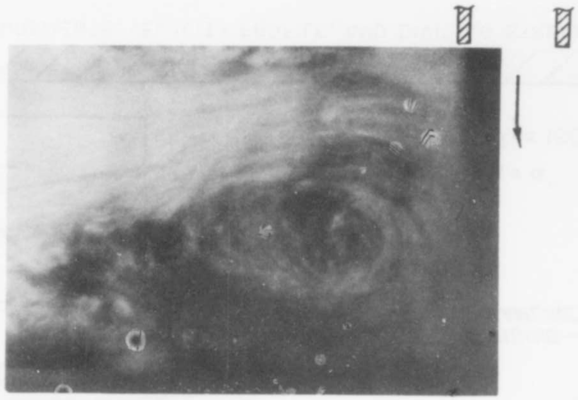
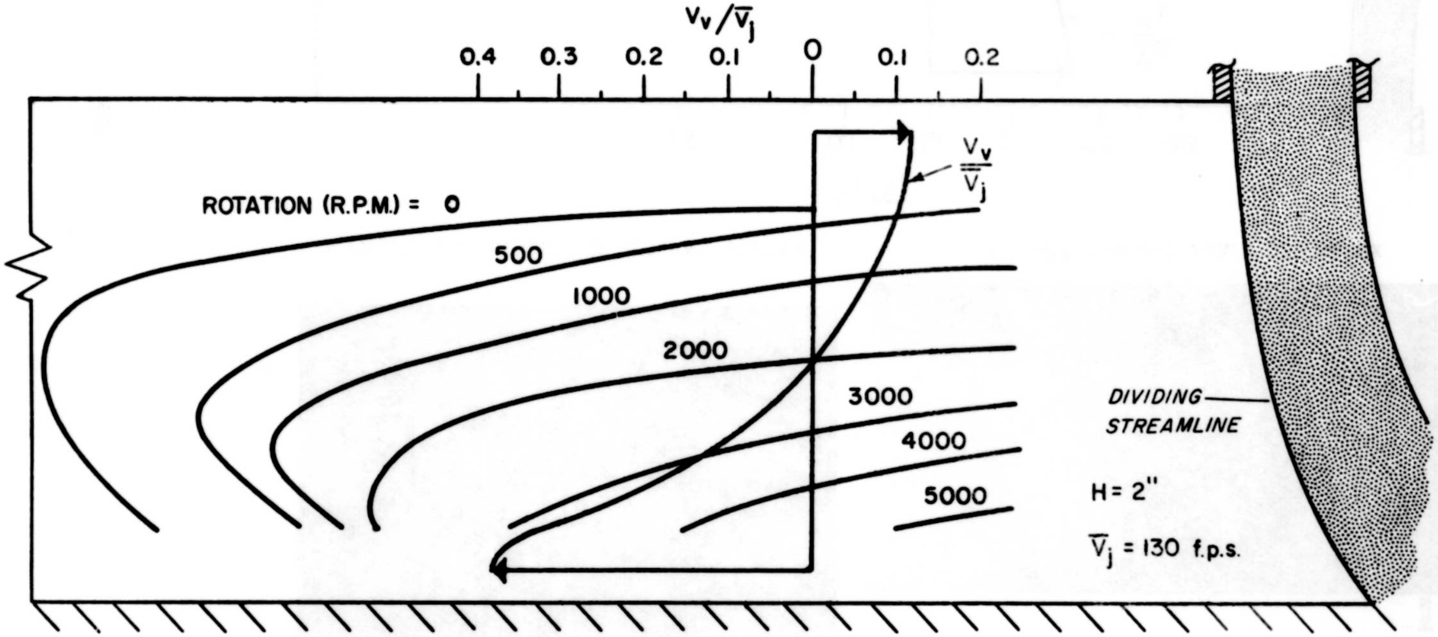
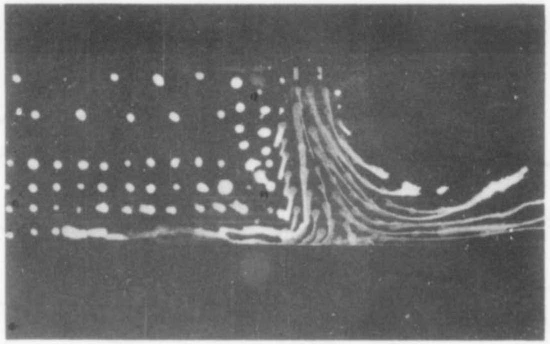


b. PHOTOGRAPHIC VIEW OF VORTEX



c. SKETCH SHOWING VORTICITY MEASUREMENTS, VELOCITY PROFILE, AND DIVIDING STREAMLINE

FIGURE 10 – DESCRIPTION OF JET AND VORTEX FOR $\overline{H}$ = 4



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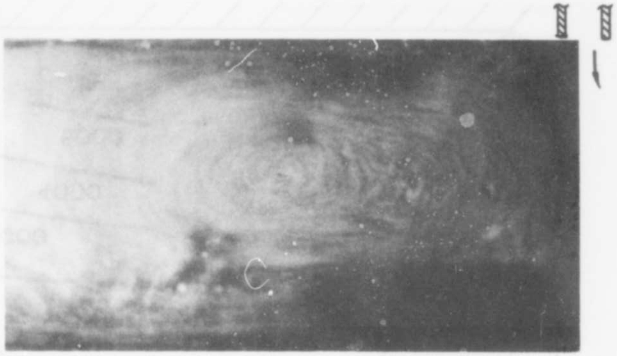
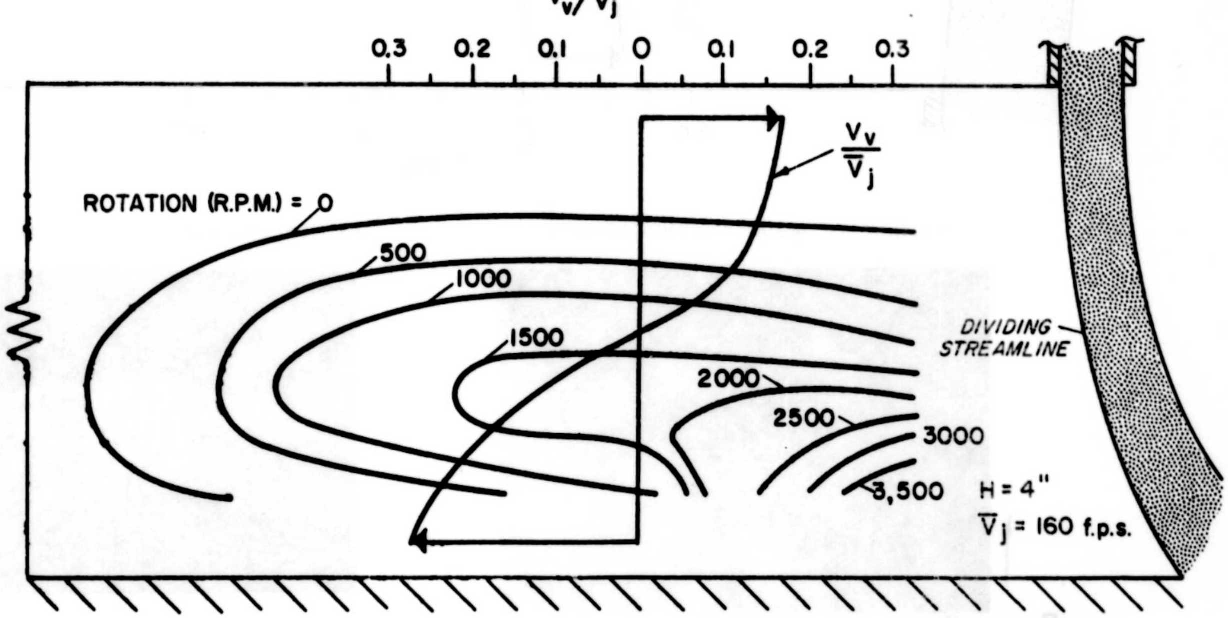


b. PHOTOGRAPHIC VIEW OF VORTEX



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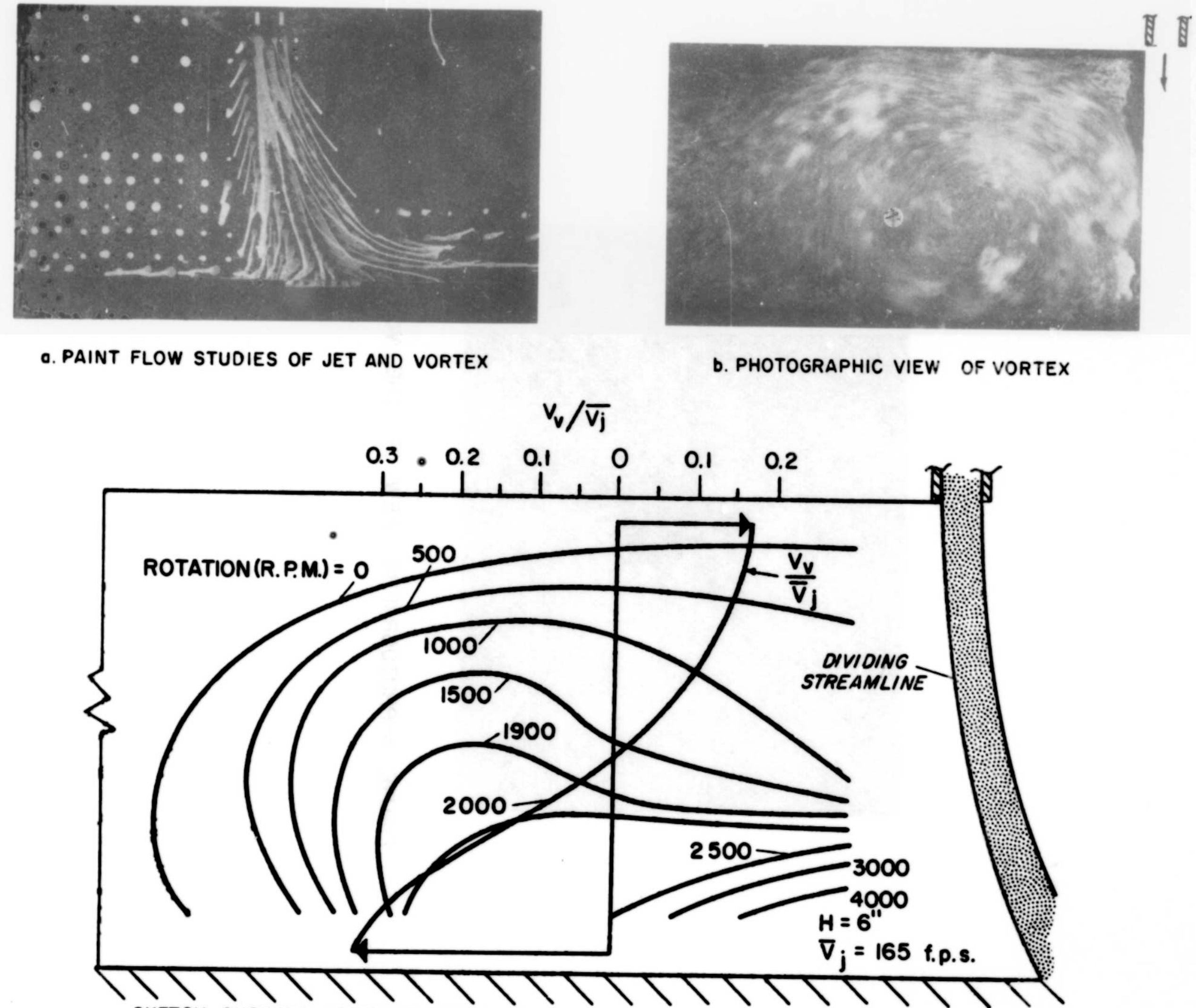
a. PAINT FLOW STUDIES OF JET AND VORTEX

b. PHOTOGRAPHIC VIEW OF VORTEX

c. SKETCH SHOWING VORTICITY MEASUREMENTS, VELOCITY PROFILE, AND DIVIDING STREAMLINE

FIGURE 12 – DESCRIPTION OF JET AND VORTEX FOR $\overline{H}$ = 12

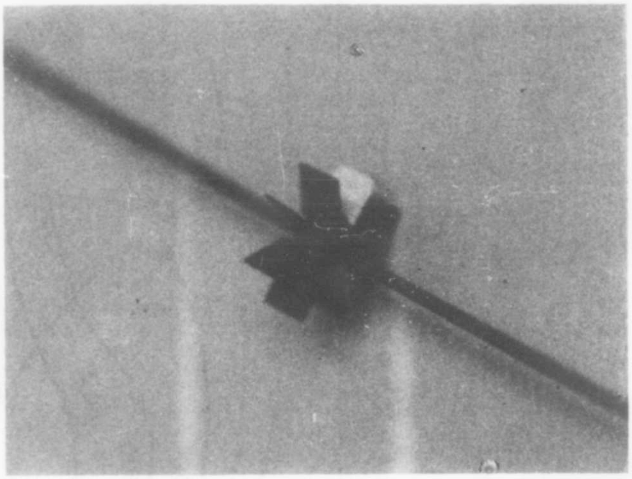

FIGURE 13-PHOTOGRAPHIC VIEW OF THE VORTICITY METER

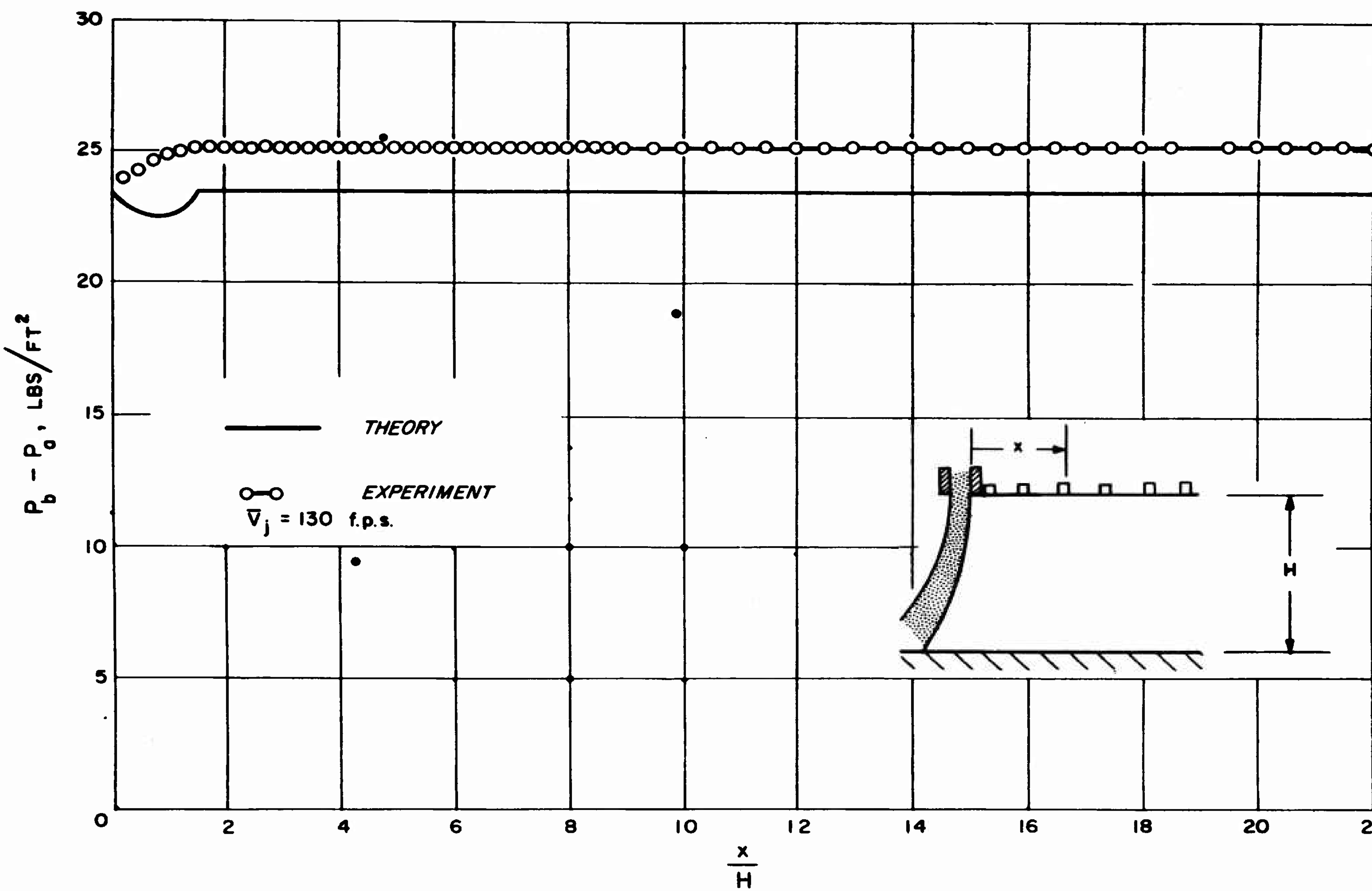

FIGURE 14 - PRESSURE DISTRIBUTION ON BASE PLATE FOR $\overline{H}$ = 2
($t = \frac{1}{2}''$)

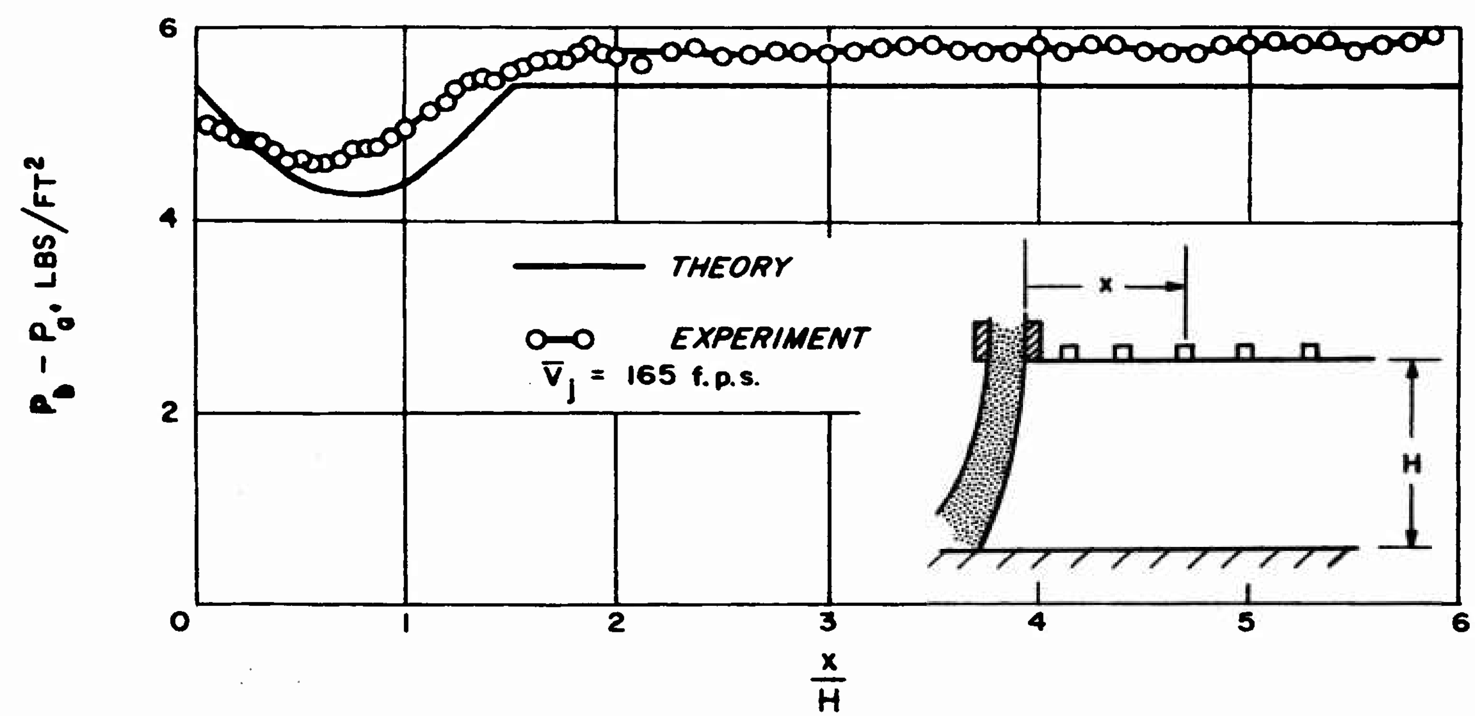

FIGURE 15 – PRESSURE DISTRIBUTION ON BASE PLATE FOR $\overline{H} = 8$
$(t = \frac{1}{2}'')$

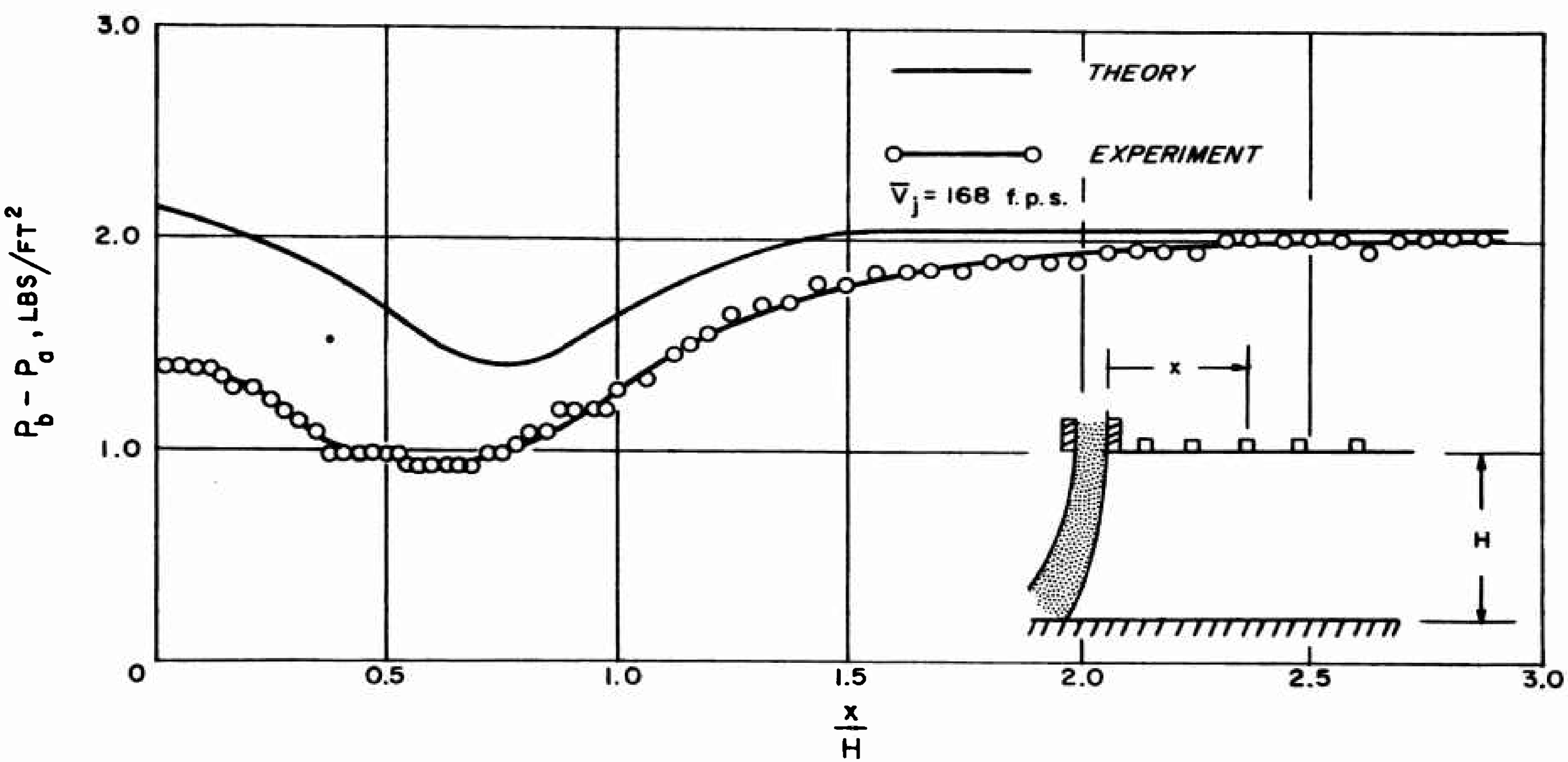

FIGURE 16 – PRESSURE DISTRIBUTION ON BASE PLATE FOR $\bar{H}$ = 16

($t = \frac{1}{2}$")

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Unclassified Report

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